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Bioenergy strategies under climate change: A stochastic programming approach

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ABSTRACT

The replacement of nuclear power with renewable energy sources is the main theme of Taiwanese energy policy. While nuclear power provides approximately 16% of total electricity supply, investigation of whether renewable energy could generate sufficient electricity to replace nuclear power becomes an important research question. Bioenergy, whose development is highly dependent on stable supply of agricultural commodities and residuals, is of particular interest to Taiwanese government because a significant amount of cropland is currently available. However, change in past climate is evidenced to alter regional temperature and precipitation, resulting in non-neglectable influences on agricultural activities and crop production, and consequently on bioenergy production. To explore how climate change plays a role in bioenergy development, this study incorporates multiple climate change scenarios and develops a two-stage stochastic programming model to analyze Taiwan's bioenergy development under different market conditions. The results show that under a small climate-induced crop yield change, net bioenergy production will not change a lot, while land use and agricultural resource allocation could vary considerably. In addition, at higher GHG prices, ethanol will not be produced and all feedstocks will be used in pyrolysis electricity, providing approximately 1.58% of total energy demand. The result also indicates that a desired level of carbon emission can be achieved, but high fluctuation of government expenses on supporting policies may occur when climate impacts are uncertain. Based on our findings, bioenergy alone is not able to provide enough electricity if nuclear power plants are shut down, and collaborative development of other renewable energy such wind power and solar energy may be required.

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1. Introduction

Taiwan, a tiny island situated in the Pacific Ocean, has very little fossil fuel stock, and more than 97% of Taiwan's energy must be imported (Chen et al., 2011). Because Taiwan is highly reliable on foreign fossil fuels, it is very vulnerable to high energy prices and market distortions in the world energy market. Therefore, lack of energy security has long been a serious problem facing Taiwan. Meanwhile, intensive use of fossil fuels have caused global climate shift, causing many direct and indirect adverse effects such increased probability of hurricanes, ocean level rise, and dissertation (Guieysse et al., 2013; IPCC, 2007; Marta et al., 2012; McCarl et al., 2007; McDonald et al., 2006), and thus there is a necessity for Taiwan to find solutions to alleviate the impacts from both energy and environmental aspects.

An even worse situation happens when Taiwanese government announces that, due to the concerns of radioactive substances disposal, they are going to replace all nuclear power by renewable energy by or before 2025. To reduce the dependence on fossil fuels and nuclear power, immediate acquisition of economically and environmentally feasible renewable energy sources becomes a high priority of this region; otherwise a shortage on electricity supply could occur at any time. Currently the nuclear power plants provide approximately 16% or 35 billion kWh of Taiwan's total electricity and it is an important and emergent issue to examine that to what extent the renewable energy can be an effective substitute.

Among all renewable energy alternatives, bioenergy is attractive to Taiwanese government because currently there is approximately one-third of Taiwan's cropland being setting aside, providing a significant amount of land for potential bioenergy development.

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Since bioenergy is generally considered to mitigate climate change by sequestering carbon dioxide (CO_2) emissions, and to enhance energy security by providing domestically produced energy, it is of particular interest to Taiwan. Before we wholeheartedly embrace bioenergy, the primary goal of bioenergy development should be defined in advance. Kung and Zhang (2015) show that the types of bioenergy must be taken into account prior to its development because maximum amount of bioenergy production generally does not come with the highest greenhouse gas (GHG) reduction. Since Taiwan is trying to find reliable energy sources to replace nuclear power, this study assumes that its goal on bioenergy development is to generate maximum amount of bioenergy production.

Climate impacts must also be incorporated in the analysis of bioenergy development because climate is a major determinant of productivity of agricultural activities. Changes in temperature and precipitation are expected to cause regions and countries to experience reductions in crop yields, and consequently reduce agricultural productivity and food security (Matsui et al., 2000; Lobell et al., 2013; Porter et al., 2014; Rosenzweig *et al.*, 2002; Sanchez et al., 2014). According to the IPCC's 2007 report, the average temperature has been increased by approximately 0.5 °C in the 20th century and McCarl (2006) shows that further increase in global climate can be up to 1.4 °C to 5.8 °C by the end of the 21st century. The economic impacts of such changes on agriculture has been studied widely (Adams et al., 1990; Asseng et al., 2011; Chang, 2002; Chang et al., 2012; Chen et al., 2016; Darwin et al., 1995; Easterling et al., 1993; Kaiser et al., 1993; McCarl, 2006; Reilly et al., 2002a, 2002b; Rosenzweig and Parry, 1994; US Climate Change Science Program, 2008), but such impacts are rarely accommodated into bioenergy studies.

To present a more realistic result that can help Taiwan's bioenergy development, this study incorporates potential changes in crop yield to evaluate the economic and environmental impacts of Taiwan's bioenergy development. Specifically, this study explores the net production ethanol and pyrolysis-based electricity, GHGs reductions, land-use changes, and resource allocations by accommodating multiple bioenergy technologies and energy crops into a two-stage stochastic programming model. Possible effects from changes in gasoline, coal, and GHG prices are also examined under different IPCC climate change projections.

The study makes several contributions. First, the potential influences of climate change on Taiwan's bioenergy development among different bioenergy production technologies are clearly illustrated. Second, the potential cultivar shift and resource reallocation depicted by this study provide a base for researchers who are interested in long-run bioenergy development. Third, it clearly presents the changes in land use and resource allocations under various market conditions and climate change scenarios. The results provide useful information to policy-makers in modifying, designing, reforming, and analyzing energy, agricultural, and environmental policies.

The study is organized as follows: "Introduction" discusses the motivations and research objectives of this study, as well as the clearly illustrated contributions. "Literature Review" presents the previous studies that are closely related to types of bioenergy, carbon offset capability, processing technology of bioenergy, and climate-induced impacts on agriculture. The last part of this section summarizes the previous works and points out how this study contributes to existing literature. "Methodology" describes the theoretical background of mathematical programming approach and depicts how such framework can be applied in this study. The stochastic version of the modeling framework is also discussed in detail. The "Results" section presents and explains findings. Economic and environmental consequences under various market operations and changes in farmers' behavior under different environmental risks are fully discussed. Some policy implications are also illustrated. "Conclusions" summarizes the research objective, modeling framework, scientific findings, limitations, and future research possibilities.

2. Literature review

Switching to low-carbon fuels such as bioenergy, wind power, hydropower, and solar energy is of high priority to mitigate the speed of global climate shift (Fargione et al., 2008). Renewable energy reduces the dependency on exhaustible fossil fuels, and ultimately improves the energy security of a country/region (Chen et al., 2011). According to Taiwan's latest energy planning, all nuclear power plants will be shut down by or before 2025, which is very likely to result in significant deficiency in energy supply in the near future.[1] Therefore, increasing production of domestically produced energy is extremely important for Taiwan to fulfill the energy demand and to ensure sustainable social development. Among all renewable energy alternatives, extraordinary attention has been paid on bioenergy development in the recent decade (Tso and Su, 2009). Prior to the 21st century, it was not an attractive opinion because a large-scale development of bioenergy requires a substantial amount of land, but Taiwan has no access to additional cropland. Nevertheless, after participation with World Trade Organization (WTO) in 2005, more than 280,000 ha (ha) of total cropland has been released due to the lower competition power of domestic agricultural commodities, making bioenergy production a feasible possibility (Chen et al., 2011).

Bioenergy usually takes liquid form such as bioethanol and biodiesel, or non-liquid form such as bioelectricity. Bioethanol in general is used to blend with gasoline in transportation system while bioelectricity reduces the use of coal (McCarl, 2006). Although they are domestically produced renewable energy that can enhance energy security (Chen et al., 2011; Kung et al., 2014), whether the reduction of CO_2 emissions may be achieved depends on how it is produced (Fargione et al., 2008). As pointed out by Searchinger et al. (2008), occurrence of deforestation and a sudden change in land use may eventually increase CO_2 emissions. To avoid the adverse effects such as fluctuation on international commodity markets and food crisis, second-generation biofuel such as cellulosic ethanol and pyrolysis-based electricity that have satisfactory level of energy conversion rate are then developed (Arvizu, 2008; Campiche et al., 2010; Kung and Zhang, 2015).

Because climate change is very likely to change regional temperature and precipitation and bioenergy is primarily produced from agricultural commodities/residuals, changes in agricultural activity thus will inevitably alter bioenergy production and affect the effectiveness of climate change mitigation. Previous studies have been investigating the agronomic effects resulted by climate change, (Asseng et al., 2011; Chang, 2002; Chang et al., 2012; Chen et al., 2016; Darwin et al., 1995; Kaiser et al., 1993; McCarl, 2006; Reilly et al., 2002a, 2002b), but their results have not been incorporated into bioenergy studies. For instance, climate change influences on crop yield response (Chen et al., 2016; Iizumi et al., 2013; Liu et al., 2014; Lobell and Burke, 2010; Lobell et al., 2012; Shuai et al., 2013a, 2013b), conventional bioenergy studies with historical crop yields (Chen et al., 2011; Kung and Zhang, 2015; Kung et al., 2014; McCarl, 2006; Schaffer and Bernauer, 2014; Tewfik et al., 2011) have been comprehensively conducted, but the relationship between climate change on crop yield and bioenergy development is not well linked. A major difference between

[1] Actually this situation already happened in 2017 summer when operations of several nuclear power plants are terminated.

this study and previous research is that this study accommodates uncertain climate-induced influences on crop yield into bioenergy development, providing a more robust and more realistic result to policy-makers.

To analyze the welfare effect from bioenergy development, an agricultural sector model that treats price endogenously, considers producers' and consumers' responses to market price signals, accommodates trade activities, and employs policy interventions has been used widely (Chang et al., 2012; Chen et al., 2011; Kung and Zhang, 2015; McCarl, 2006). Although the crop yield is possibly influenced by the climate change, its impacts on the volume of international trade and the size of international adjustments are usually assumed insignificant (McCarl, 2006; Reilly, 1995). Therefore, all other factors in non-agricultural sectors are also assumed to be constant in our analytical framework, but the potential crop yield changes, derived by Chang (2002) and Chang et al. (2012) (as shown in Table 1), are stochastically designed in this study to depict bioenergy and other social-economic effects. The details are fully explained and discussed in the methodology.

3. Methodology

The modeling framework of the agricultural sector model (ASM) is derived from the theoretical analysis of Samuelson (1952), the empirical structure of McCarl and Spreen (1980), and a number of subsequent studies (Adams et al., 1990; Chang et al., 2012; McCarl, 2006). As demonstrated by McCarl and Spreen (1980), a price endogenous model is suitable for policy analysis because it can represent the economic system in a perfect competition market. Since then the price endogenous modeling framework is intensively applied in many environmental and resource studies such as acid rain (Adams et al., 1992), soil protection (Chang et al., 1992), renewable energy (Tyner, 1979), climate shift (Adams et al., 1998, 1999; McCarl, 2007; Reilly et al., 2002a), ozone (Hamilton et al., 1985), GHG mitigation (Adams et al., 1995; McCarl and Schneider, 2000), and policy evaluation (Chang et al., 1992; Coble et al., 1992).

3.1. Basics of TASM

Chen and Chang (2005) extend the basic ASM framework and develop the Taiwan Agricultural Sector Model (TASM) to evaluate how agricultural policy influences crop production and market operations. Thereafter this empirical structure is applied to Taiwan's agricultural, environmental, and land-use analysis (Chang et al., 2012; Chen and Chang, 2005; Chen et al., 2011; Kung et al., 2013). This modeling framework adopts the structure of perfect competition by assuming individual producers and consumers to be price-takers in all markets. Input supply and rice-dependent product demand curves are also incorporated. In TASM the production activities of every commodity and crop and livestock mix activities are specified at the sub-regional level while the inputs markets such as labor, fertilizer, and irrigation are specified at regional level. In current version more than 120 agricultural commodities are accommodated in TASM and approximately 87% of Taiwan's total agricultural product value is incorporated in this model.

Table 1
Estimates of crop yield change under HADCM projections.

	Scenario A	Scenario B
Rice	−0.70%	−1.60%
Wheat	0.20%	0.10%
Corn	−1.20%	−3%
Soybean	4%	3%
Sorghun	7%	18%
Peanuts	−0.03%	0.95%
Sweet-Potatoes	−2.26%	−2.76%
Potatoes	0.97%	3.17%
Tea	−1.65%	−1.45%
Cane for process	1.03%	−1.87%
Cane for fresh	1.03%	−1.87%

Source: Chang et al. (2012).

3.2. Toward a stochastic version of TASM

To reflect the climate-induced impacts on crop yields, it is necessary to modify such uncertain influences into original TASM framework. To accomplish this task, this study employs the stochastic programming with recourse (SPR) formulation illustrated in Lambert et al. (1995) and Chen and McCarl (2000). To reflect variability of crop yields, the modified model contains more than one state of nature while the commodity demand in each state of nature remains constant. Under the stochastic formulation, farmers are assumed to make planting decisions before they know actual yields, and their objective function includes the revenues of each state of nature to reflect the variability associated with planting decisions. In the second state of nature, the true crop yields become certain while the resource endowments remain fixed, implying the farmers must adjust their harvesting activities in accordance to the reality. With such formulation, the analytical framework is then extended to a two-stage approach by embedding farmers' planting decision in the first stage and by constraining the supply and demand balances in the second stage. The stochastic TASM then can be algebraically depicted as follows:

$$\begin{aligned} Max\ W = \sum_s \rho(s)*\Bigg\{ & \sum_i \int \psi(Q_{is})dQ_{is} - \sum_k \int \alpha_k(L_k)dL_k \\ & - \sum_k \int \beta_k(R_k)dR_k - \sum_i \sum_k C_{ik}X_{ik} \\ & + \sum_i \int ED\left(Q_{is}^M\right)dQ_{is}^M + \sum_i \int EXED(TRQ_{is})dTRQ_{is} \\ & - \sum_i \int ES\left(Q_i^X\right)dQ_i^X + \sum_i \left[tax_i*Q_{is}^M + outtax_i*TRQ_{is}\right] \\ & \times \Bigg\} + \sum_i P_i^G*Q_i^G + \sum_k P^L*AL_k + \sum_j SUB_j*AL_j \\ & - P_{GHG}*\sum_g GWP_g*GHG_g \end{aligned} \tag{1}$$

Subject to

$$Q_{is} + Q_{is}^X + Q_i^G - \sum_k Y_{iks}*(1 + CCYIELD_i)*X_{ik} - \left(Q_{is}^M + TRQ_{is}\right) \leq 0 \quad \forall i,s \tag{2}$$

$$\sum_i X_{ik} + AL_k - L_k \leq 0 \quad \forall k \tag{3}$$

$$\sum_i f_{ik}X_{ik} - R_k \leq 0 \quad \forall k \tag{4}$$

$$\sum_{i,k} E_{gik}X_{ik} - GHG_g \leq 0 \quad \forall g \tag{5}$$

Where.

s	State of nature s
Q_i	Domestic demand of i^{th} product
Q_i^G	Government purchases quantity for price supported i^{th} product
Q_i^M	Import quantity of i^{th} product
Q_i^X	Export quantity of i^{th} product
$\omega(Q_i)$	Inverse demand function of i^{th} product
P_i^G	Government purchase price on i^{th} product
C_{ik}	Purchased input cost in k^{th} region for producing i^{th} product
X_{ik}	Land used for i^{th} commodities in k^{th} region
L_k	Land supply in k^{th} region
$\alpha_k(L_k)$	Land inverse supply in k^{th} region
R_k	Labor supply in k^{th} region
$\beta_k(R_k)$	Labor inverse supply in k^{th} region
P^L	Set-aside subsidy
AL_k	Set-aside acreage in k^{th} region
$ED(Q_i^M)$	Inverse excess import demand curve for i^{th} product
$ES(Q_i^X)$	Inverse excess export supply curve for i^{th} product
TRQ_i	Import quantity exceeding the quota for i^{th} product
$EXED(TRQ_i)$	Inverse excess demand curve of i^{th} product that the import quantity is exceeding quota.
tax_i	Import tariff for i^{th} product
$outtax_i$	Out-of-quota tariff for i^{th} product
Y_{ik}	Per hectare (ha) yield of i^{th}commodity produced in k^{th} region
$f_{ik}Y_{ik}$	Labor required per hectare of commodity i in region k
f_{ik}	Labor required per hectare of commodity i in region k
SUB_j	Subsidy on planting j^{th}energycrop
EC_{jk}	Planted acreage of j^{th} energy crop ink^{th} region
P_{GHG}	Price of GHG gas
GWP_g	Global warming potential of g^{th} greenhouse gas
GHG_g	Net greenhouse gas emissions of g^{th} gas
E_{gik}	g^{th} greenhouse gas emission from i^{th} product in k^{th} region

The objective function is shown as Equation (1), representing the domestic policies and international trade activities. Equation (2) is a balance constraint ensuring the use of quantity of commodity is less than the quantity produced. Equations (3) and (4) control the land availability and other resource use, respectively. Equation (5) is the balance constraint on total emissions.

Although it has been proved that more than 94% of agricultural activities in Taiwan can be well depicted, implying it is suitable for the subsequent bioenergy analysis, some pros and cons for this modeling structure are worth mentioning. Firstly, the commodity coverage is representative because most of Taiwanese agricultural commodities are covered. With such structure, researchers can easily expand their model once they want more items to be included. Second, the model includes historical crop and livestock mix data and thus prevents the solutions from pushing agricultural activities of some crops to zero, which is very unlikely to happen. Third, all geographic regions are included and separated into major processing regions, implying the researchers can analyze the economic and environmental influences, depending on their objectives. The most important disadvantage of this partial equilibrium model is that such structure can only be applied to small regions whose production of agricultural commodities does not have considerable impacts on global markets; otherwise the model cannot be employed.

3.3. Data and scenario setup

To simulate the economic and environmental effects under various market operations, this study accommodates different gasoline price, coal price, and GHG price to examine how the changes in energy price and carbon trade price may alter the performance of bioenergy development. The ranges of gasoline and coal prices are selected from the Taiwan's historical trading prices of petroleum and thermal coal, respectively. The value from emission reduction is based on the Chicago Climate Exchange and its welfare impact is fully reflected in the objective function. The units of gasoline, coal and emission price are converted from U.S. dollars to New Taiwan dollars such as NT$ per liter, NT$ per kg, and NT$ per ton, respectively. To better reflect the true economic and environmental consequences from bioenergy production, the plant operation costs, pyrolysis costs, and input processing costs are incorporated in the annualized terms. The basic calculation of such parameters can be found from our previous studies (Kung et al., 2013). In this study the processing costs and hauling costs associated with primary and secondary agricultural commodities are further modified to reflect the potential climate-induced impacts on agricultural activities.

Data used in this study originates from various published government statistics and research reports including the Taiwan Agricultural Yearbook, Trade Statistics of the Inspectorate-General of Customs, Taiwan Agricultural Prices and Costs Monthly, Taiwan Area Agricultural Products Wholesale Market Yearbook, Production Cost and Income of Farm Products Statistics, Forestry Statistics of Taiwan, and Commodity Price Statistics Monthly. Parameters such as biomass conversion rates, emission offset capability, unit processing costs, and price elasticities are obtained from literature, personal communications and data calculation.

4. Results

4.1. Discussion

This study analyzes the bioenergy development strategies by incorporating various energy and GHG prices, along with uncertain

Table 2
Bioenergy production under crop yield changes.

Probability of yield change		Low	Moderate	High
Gasoline Price	NT/Liter	25	25	25
Coal Price	NT/kg	1.8	1.8	1.8
GHG Price	NT/ton	5	5	5
Scenario A2				
Ethanol Production	1000 L	132,600.0	130,000.0	132,600.0
Pyrolysis Electricity	1000 kWh	1,836,090.1	2,057,980.8	1,836,090.1
Scenario B2				
Ethanol Production	1000 L	132,600.0	130,000.0	132,600.0
Pyrolysis Electricity	1000 kWh	1,836,090.1	2,061,388.2	1,834,995.7

crop yield change. The results, as shown in Table 2, indicate that under the base price conditions approximately 1.8 billion kWh electricity and 132 million liters of ethanol can be produced, accounting for the 0.92% of annual electricity demand and 39.6% of blended gasoline demand, respectively. In this case, the risk of climate-induced impacts on crop yields seems to have a very small influence on bioenergy production. When risk of climate impacts is low, planting decisions made by farmers will not take such risk into account and bioenergy production is therefore not affected. With higher possibility that climate-induced crop yield change occurs, planting decisions alters and thus bioenergy production may slightly fluctuate by 0.1%–0.2%.

To propose a feasible and reasonable bioenergy planning, it is crucial to determine what factors could have the most significant influences on bioenergy production because only with such information the appropriate policies may be designed. Table 3 shows the bioenergy consequences under various market operations. The results show that when gasoline price is NT$20 per liter, ethanol production shrink to 49% of base production. Meanwhile, the electricity generation increases to 2.49 billion kWh or by 36%. If we take the crop yield change into account, the ethanol production will reduce to 60–64 million liters and the electricity will increase by another 265 million kWh.

The results also indicate that the change in energy prices have higher influences than crop yield change, implying that market operations play a more important role in bioenergy development instead of environmental risk. It is clear that competition exists among all bioenergy technologies. When pyrolysis becomes an available alternative, conventional co-firing will not be selected and all electricity is generated from pyrolysis. In addition, when GHG price is high, ethanol turns out to be non-competitive, regardless of gasoline prices. This is because the emission offset ability is generally lower than that of electricity-based bioenergy. The results show that bioenergy can provide up to 2.94 billion kWh, accounting for 1.47% of Taiwan's annual electricity demand. It is clear that to replace nuclear power plants it is not sufficient to solely rely on the bioenergy, and other renewable energy technologies such as wind farm and solar energy must be considered simultaneously. All simulation results are provided in Appendix.

Although the priority for Taiwan to develop bioenergy is to maximize domestically produced renewable energy, it is worth showing the climate change mitigation consequences from bioenergy production. Table 4 shows the result. In most cases more than 99.9% of emission offsets come from electricity. Only when

Table 3
Bioenergy production under various market conditions.

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	20	20	20	25	25	25
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	5	5	5	5	5	5
Scenario A2							
Ethanol Production	1000 L	68,226.9	60,178.1	64,704.0	132,600.0	130,000.0	132,600.0
Pyrolysis Electricity	1000 kWh	2,497,300.0	2,762,500.0	2,497,300.0	1,836,090.1	2,057,980.8	1,836,090.1
Scenario B2							
Ethanol Production	1000 L	68,226.9	59,957.7	64,605.5	132,600.0	130,000.0	132,600.0
Pyrolysis Electricity	1000 kWh	2,497,300.0	2,762,500.0	2,497,300.0	1,836,090.1	2,061,388.2	1,834,995.7
Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	20.0	20.0	20.0	25.0	25.0	25.0
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	50.0	50.0	50.0	50.0	50.0	50.0
Scenario A2							
Ethanol Production	1000 L	5200.0	5200.0	5200.0	5200.0	5200.0	5200.0
Pyrolysis Electricity	1000 kWh	2,758,451.5	2,752,872.7	1,553,819.8	1,525,847.5	2,782,742.7	2,766,548.5
Scenario B2							
Ethanol Production	1000 L	5200.0	5200.0	5200.0	5200.0	5200.0	5200.0
Pyrolysis Electricity	1000 kWh	2,758,451.5	2,762,500.0	2,766,548.3	1,525,847.5	2,769,721.9	2,766,548.5
Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	20.0	20.0	20.0	25.0	25.0	25.0
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	50.0	50.0	50.0	50.0	50.0	50.0
Scenario A2							
Ethanol Production	1000 L	5200.0	5200.0	5200.0	5200.0	5200.0	5200.0
Pyrolysis Electricity	1000 kWh	2,935,084.5	2,938,566.2	2,902,537.0	2,935,084.5	2,938,566.2	2,902,537.0
Scenario B2							
Ethanol Production	1000 L	5200.0	5200.0	5200.0	5200.0	5200.0	5200.0
Pyrolysis Electricity	1000 kWh	2,935,084.5	2,938,416.1	2,940,321.6	2,935,084.5	2,938,416.1	2,940,321.6

Table 4
Climate change mitigation potential.

Probability of Yield Change		Low	High	Low	High	Low	High
Gasoline Price	NT/Liter	20	20	20	20	20	20
Coal Price	NT/kg	1.8	1.8	1.8	1.8	3.6	3.6
GHG Price	NT/ton	50	50	5	5	5	5
Scenario A2							
Net Reduction	ton	2,623,870.3	2,967,285.0	1,677,179.1	1,676,784.5	2,292,770.8	2,227,980.6
Emission Offset	Ton/ha	20.38	23.05	14.04	14.06	18.42	18.18
Carbon @SWP	%	99.98%	99.98%	99.54%	99.57%	99.97%	99.97%
Carbon @Ethanol	%	0.02%	0.02%	0.46%	0.43%	0.03%	0.03%
Scenario B2							
Net Reduction	ton	2,623,870.3	2,592,931.2	1,677,179.1	1,676,773.5	2,292,770.8	2,227,544.7
Emission Offset	Ton/ha	20.38	20.14	14.04	14.06	18.42	18.18
Carbon @SWP	%	99.98%	99.98%	99.54%	99.57%	99.97%	99.97%
Carbon @Ethanol	%	0.02%	0.02%	0.46%	0.43%	0.03%	0.03%
Probability of Yield Change		Low	High	Low	High	Low	High
Gasoline Price	NT/Liter	20	20	40	40	40	40
Coal Price	NT/kg	3.6	3.6	1.8	1.8	1.8	1.8
GHG Price	NT/ton	50	50	5	5	50	50
Scenario A2							
Net Reduction	ton	2,569,210.9	2,550,953.5	1,113,609.8	1,089,602.5	2,609,950.1	2,966,899.1
Emission Offset	Ton/ha	19.96	19.81	9.28	9.10	20.27	23.05
Carbon @SWP	%	99.98%	99.98%	98.28%	98.24%	99.98%	99.98%
Carbon @Ethanol	%	0.02%	0.02%	1.72%	1.76%	0.02%	0.02%
Scenario B2							
Net Reduction	ton	2,569,210.9	2,539,285.4	1,113,609.8	1,088,921.8	2,582,128.5	2,592,857.6
Emission Offset	Ton/ha	19.96	19.72	9.28	9.09	20.06	20.14
Carbon @SWP	%	99.98%	99.98%	98.28%	98.24%	99.98%	99.98%
Carbon @Ethanol	%	0.02%	0.02%	1.72%	1.76%	0.02%	0.02%

GHG and coal prices are low but gasoline price is high, ethanol can offset approximately 19,200 tons of CO_2. In the best case, the net emission offset could achieve 3 million tons, accounting for 1.22% of Taiwanese total emission. Per hectare emission offset can be as high as 23.05 tons, which is a satisfactory rate. However, if a major land-use change occurs, it is important to consider the GHG consequences associated with the alteration of cultivation patterns and land emissions.

Development of bioenergy involves many aspects, and government supporting policy is a typical one. The results point out that it is expensive to develop bioenergy industry. Table 5 gives the result, in which showing that in general the Taiwanese government must pay approximately NT$ 13.5 billion dollars in maintaining set-aside land, along with an additional payment on energy crop plantation. At higher GHG prices, more aside land participates with energy crop plantation and thus drives the total expenditures up. In Table 5 we find that the influences from crop yield change potentially vary the land use. When productivity of land is altered, farmers will choose to plant crops which bring them a higher expected income. Therefore, although crop yield change itself does not have direct impacts on bioenergy production, it could have considerable on land-use change and thus its influence should be incorporated, especially for the long-term planning.

Fig. 1 shows the potential changes of agricultural resource

Table 5
Government expense to support bioenergy development under various climate and market conditions.

Probability of yield change		Low	High	Low	High	Low	High
Gasoline Price	NT/Liter	20	20	20	20	20	20
Coal Price	NT/kg	1.8	1.8	1.8	1.8	3.6	3.6
GHG Price	NT/ton	50	50	5	5	5	5
Scenario A2							
SWP Subsidy	Million NT	6435.89	6435.90	5971.55	5963.11	6222.85	6127.09
SWP Ha	1000 ha	128.72	128.72	119.43	119.26	124.46	122.54
Aside Subsidy	Million NT	11,623.05	13,400.65	13,609.63	13,567.71	10,752.14	13,128.82
Scenario B2							
SWP Subsidy	Million NT	6435.89	6437.39	5971.55	5961.53	6222.85	6127.83
SWP Ha	1000 ha	128.72	128.75	119.43	119.23	124.46	122.56
Aside Subsidy	Million NT	11,623.05	11,880.29	13,609.63	13,601.98	10,752.14	12,908.11
Probability of yield change		Low	High	Low	High	Low	High
Gasoline Price	NT/Liter	20	20	40	40	40	40
Coal Price	NT/kg	3.6	3.6	1.8	1.8	1.8	1.8
GHG Price	NT/ton	50	50	5	5	50	50
Scenario A2							
SWP Subsidy	Million NT	6437.46	6437.34	5998.47	5989.18	6437.31	6435.90
SWP Ha	1000 ha	128.75	128.75	119.97	119.78	128.75	128.72
Aside Subsidy	Million NT	12,269.64	12,221.27	11,945.00	11951.32,	11,903.88	11,852.43
Scenario B2							
SWP Subsidy	Million NT	6437.46	6437.34	5998.47	5987.49	6437.36	6437.40
SWP Ha	1000 ha	128.75	128.75	119.97	119.75	128.75	128.75
Aside Subsidy	Million NT	12,269.64	12,145.66	11,945.00	11,950.68	11,903.88	13,406.44

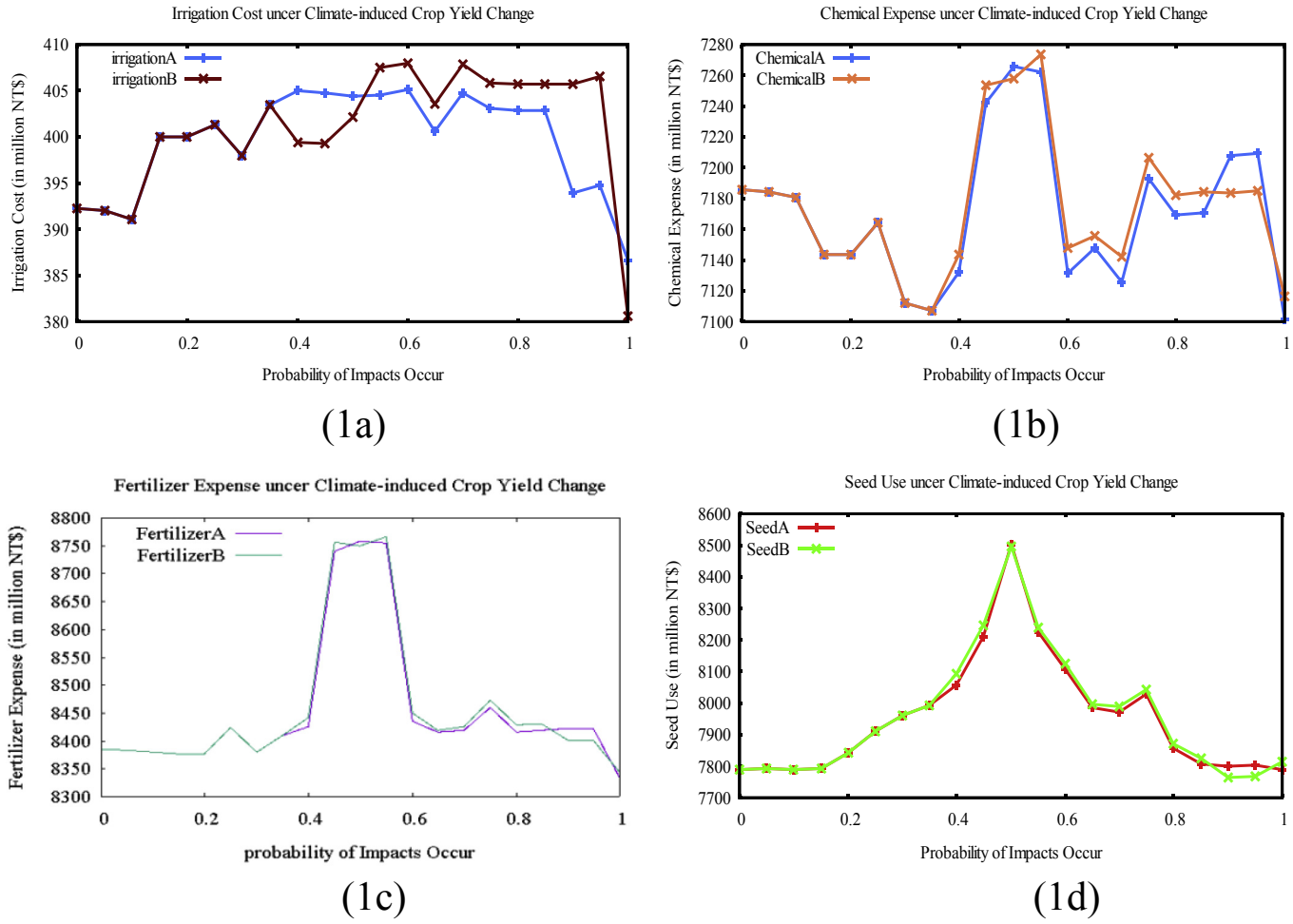

Fig. 1. Resources use under climate-induced crop yield change.

allocation. It is obvious that irrigation costs and chemical expenses could have a considerable change when possibilities of climate-induced crop yield change increase, implying that cultivars could have been deviated from the current practice, as shown in 1a and 1b. This situation occurs when the risk is most uncertain (i.e., farmers don't know whether the crop yield change may occur), cultivation activities may be altered significantly, as indicated in Fig. 1c and d. When crop yield becomes more certain, total expenses on fertilizers and seeds will remain in a more smoothly patterns, implying the land will be still engaged in agricultural activities with new cultivars. That is, the farmers are probably not to switch their cultivars when crop yield change is not likely happen, and when the risk increases, they may choose to plant other crops or even simply set their land aside, and that's why we observe a fluctuation on resources uses.

4.2. Policy implications

The study employs a stochastic programming approach to explore the relationships among bioenergy production, production technologies, market conditions, GHG prices, and climate-induced crop yield change. Based on the results, some policy implications can be derived:

(1) Influences of climate-induced crop yield change could be important. The results show that the bioenergy production is insensitive to crop yield change, implying that development of bioenergy should focus on markets factors such as energy and GHG prices. However, the results do not mean that the potential crop yield change can be neglected by policy-makers. As illustrated in Fig. 1, even with a small change in crop yield, the potential land use may alter considerably. To ensure the sustainable development of bioenergy, a stable supply of feedstocks is a premise and thus an appropriate land policy and supporting policy may be required. Another important point could arise when actual crop yield change is larger than projected scenarios, and under such circumstance, the potential change in land use and resource allocation may be even greater. Then it would be necessary to investigate their impacts on supply stability of feedstocks, and consequently on bioenergy production.

(2) Farmers' behavior could play an important role in bioenergy development. As indicated in the results, farmers will adjust their practice in face of crop yield change. If such risk is uncertain and they must make a guess, then a large-scale alteration of land use would occur. Under this circumstance, land may be turned into idle or simply switch to other activities. Although such change may not hamper bioenergy development because newly idle land can still participate in the energy crop plantation and consequently increase the net bioenergy production, the whole society pay the costs in terms of government subsidy. For this reason, a proper

monitoring of climate change and accurate estimation of crop yield changes could be important for guiding plantation decisions and supporting bioenergy development.

(3) The market conditions are crucial for successful development of bioenergy. Results show that bioenergy production can fluctuate considerable under various energy and GHG prices. If Taiwan aims to replace nuclear power by renewable energy, maintaining a desired level of energy is keyed to enhance bioenergy production. As Taiwan has no control on such prices, some economic incentives such as tax credit or direct subsidy may be used to stimulate bioenergy production. Because such incentives may be at costs of whole society, they must be appropriately designed.

5. Conclusions

Taiwan has just announced that before 2025 all of its nuclear power will be replaced by renewable energy. Because nuclear power plants provide more than 16% of total electricity demand, it is necessary to examine how renewable energy can help. Among all renewable energy alternatives bioenergy is of particular interest because approximately one-third of cropland has been released, making bioenergy feasible in such a small island. In addition, development of bioenergy might be affected by the climate-induced crop yield change, and thus the climate impact is included. This study develops a two-stage stochastic programming model to analyze the bioenergy potential and its economic and environmental consequences under various market conditions and climate change scenarios. The results will be helpful to policy-makers to understand how climate change affects Taiwan's bioenergy development by depicting its production and to what extent bioenergy can substitute nuclear power.

The results indicate that both pyrolysis-base electricity and ethanol production are not significantly influenced by a small change in crop yield. Instead, a considerable change in land use and resource allocation can occur. The study shows that bioenergy production is primarily affected by energy and GHG prices, and ethanol will be produced only at low GHG prices. Therefore, the results imply that if Taiwan is going to replace nuclear power by bioenergy, setting a high carbon price can encourage production of bioelectricity, otherwise ethanol will grad a portion of feedstocks and reduce net electricity supply from renewable sources. However, it is worth noticing that even with the most optimistic scenario, bioelectricity can only provide about 1.58% of Taiwan's electricity demand, which is far below the electricity generated from nuclear power. Therefore, other renewable technologies such as wind farm and solar energy must be considered simultaneously to achieve this goal.

The framework of this study is based on a static and stochastic analysis. Therefore, the results cannot tell whether short-term changes in land and resource use can have long-term effects on bioenergy. In addition, the future climate pattern may be very different from IPCC projected scenarios, and once its impacts on agriculture is larger than used in this study, the effectiveness of bioenergy development in Taiwan must be re-evaluated. Another factor that might affect the results of this study is that the Taiwanese government is also considering to develop solar energy on these idle land, which may reduce the net bioenergy production and associated economic and environmental effects portrayed in this study. Further investigation of joint competition among different renewable energy technologies may be needed.

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Appendix

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	20	20	20	25	25	25
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	50	50	50	50	50	50
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,758,451.47	2,752,872.71	1,553,819.76	1,525,847.54	2,782,742.67	2,766,548.53
Net Electricity	1000 kWh	3,037,484.31	3,031,905.55	1,832,852.6	1,804,880.38	3,061,775.51	3,045,581.37
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,623,287.86	2,610,897.65	2,966,702.58	3,003,557.38	2,601,681.49	2,592,561.61
Net Reduction	ton	2,977,178.03	2,964,787.81	3,320,592.74	3,357,447.54	2,955,571.66	2,9464,51.78
SWP Subsidy	Million NT	6435.89	6435.89	6435.9	6435.9	6435.89	6435.9
SWP Planted Ha	1000 ha	128.72	128.72	128.72	128.72	128.72	128.72
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,758,451.47	2,762,500	2,766,548.28	1,525,847.54	2,769,721.93	2,766,548.53
Net Electricity	1000 kWh	3,037,484.31	3,041,532.84	3,045,581.12	1,804,880.38	3,048,754.77	3,045,581.37
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,623,287.86	2,607,924.32	2,592,348.76	3,003,557.38	2,605,697.39	2,592,562.25
Net Reduction	ton	2,977,178.03	2,961,814.49	2,946,238.93	3,357,447.54	2,959,587.56	2,946,452.42
SWP Subsidy	Million NT	6435.89	6435.9	6437.39	6435.9	6435.9	6435.9
SWP Planted Ha	1000 ha	128.72	128.72	128.75	128.72	128.72	128.72

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	30	30	30	35	35	35

(*continued on next page*)

(*continued*)

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	50	50	50	50	50	50
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	1,525,841.69	2,782,742.67	2,766,548.53	2,842,616.34	1,856,509.19	2,766,548.22
Net Electricity	1000 kWh	1,804,874.53	3,061,775.51	3,045,581.37	3,121,649.18	2,135,542.03	3,045,581.06
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	3,003,559.18	2,601,681.5	2,592,561.58	2,597,041.22	2,887,168.91	2,592,293.19
Net Reduction	ton	3,357,449.35	2,955,571.66	2,946,451.75	2,950,931.39	3,241,059.07	2,946,183.35
SWP Subsidy	Million NT	6435.9	6435.89	6435.9	6437.29	6437.31	6437.31
SWP Planted Ha	1000 ha	128.72	128.72	128.72	128.75	128.75	128.75
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	1,525,841.69	2,769,721.93	2,766,548.51	2,842,616.34	1,863,126.48	2,766,548.24
Net Electricity	1000 kWh	1,804,874.53	3,048,754.77	3,045,581.35	3,121,649.18	2,142,159.32	3,045,581.08
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	3,003,559.18	2,605,697.39	2,592,548.33	2,597,041.22	2,885,172.81	2,592,308.77
Net Reduction	ton	3,357,449.35	2,959,587.56	2,946,438.5	2,950,931.39	3,239,062.98	2,946,198.94
SWP Subsidy	Million NT	6435.9	6435.9	6435.99	6437.29	6437.38	6437.32
SWP Planted Ha	1000 ha	128.72	128.72	128.72	128.75	128.75	128.75

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	40	40	40	20	20	20
Coal Price	NT/kg	1.8	1.8	1.8	3.6	3.6	3.6
GHG Price	NT/ton	50	50	50	50	50	50
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,802,680.09	2,734,842.85	1,555,066.65	2,935,084.53	2,938,566.18	2,902,537.03
Net Electricity	1000 kWh	3,081,712.92	3,013,875.69	1,834,099.49	3,214,117.37	3,217,599.02	3,181,569.87
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,609,367.73	2,616,256.09	2,966,316.65	2,568,628.46	2,553,410.91	2,550,371.08
Net Reduction	ton	2,963,257.9	2,970,146.26	3,320,206.82	2,922,518.62	2,907,301.07	2,904,261.25
SWP Subsidy	Million NT	6437.31	6437.42	6435.9	6437.46	6437.4	6437.34
SWP Planted Ha	1000 ha	128.75	128.75	128.72	128.75	128.75	128.75
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,887,307.15	2,732,984.84	2,766,807.39	2,935,084.53	2,938,416.05	2,940,321.56
Net Electricity	1000 kWh	3,166,339.99	3,012,017.68	3,045,840.23	3,214,117.37	3,217,448.88	3,219,354.4
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,581,546.09	2,616,829.3	2,592,275.16	2,568,628.46	2,553,463.58	2,538,703.04
Net Reduction	ton	2,935,436.26	2,970,719.47	2,946,165.33	2,922,518.62	2,907,353.75	2,892,593.21
SWP Subsidy	Million NT	6437.36	6437.42	6437.4	6437.46	6437.42	6437.34
SWP Planted Ha	1000 ha	128.75	128.75	128.75	128.75	128.75	128.75

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	25	25	25	30	30	30
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	50	50	50	50	50	50
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,935,084.53	2,938,566.18	2,902,537.03	2,935,084.53	2,937,535.5	2,902,537.03
Net Electricity	1000 kWh	3,214,117.37	3,217,599.02	3,181,569.87	3,214,117.37	3,216,568.34	3,181,569.87
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,568,628.46	2,553,410.91	2,550,371.08	2,568,628.46	2,553,743.55	2,550,371.08
Net Reduction	ton	2,922,518.62	2,907,301.07	2,904,261.25	2,922,518.62	2,907,633.71	2,904,261.25
SWP Subsidy	Million NT	6437.46	6437.4	6437.34	6437.46	6437.44	6437.34
SWP Planted Ha	1000 ha	128.75	128.75	128.75	128.75	128.75	128.75
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,935,084.53	2,938,416.05	2,940,321.56	2,935,084.53	2,938,416.05	2,940,321.56
Net Electricity	1000 kWh	3,214,117.37	3,217,448.88	3,219,354.4	3,214,117.37	3,217,448.88	3,219,354.4
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,568,628.46	2,553,463.58	2,538,703.04	2,568,628.46	2,553,463.58	2,538,703.04
Net Reduction	ton	2,922,518.62	2,907,353.75	2,892,593.21	2,922,518.62	2,907,353.75	2,892,593.21
SWP Subsidy	Million NT	6437.46	6437.42	6437.34	6437.46	6437.42	6437.34
SWP Planted Ha	1000 ha	128.75	128.75	128.75	128.75	128.75	128.75

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	35	35	35	40	40	40
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	50	50	50	50	50	50
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,935,084.53	2,937,471.15	2,902,537.03	2,758,451.42	2,937,535.5	3,065,551.11
Net Electricity	1000 kWh	3,214,117.37	3,216,503.99	3,181,569.87	3,037,484.26	3,216,568.34	3,344,583.95

(*continued*)

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,568,628.46	2,553,763.4	2,550,371.08	2,623,328.83	2,553,743.55	2,500,137.88
Net Reduction	ton	2,922,518.62	2,907,653.57	2,904,261.25	2,977,219	2,907,633.71	2,854,028.05
SWP Subsidy	Million NT	6437.46	6437.44	6437.34	6435.93	6437.44	6437.45
SWP Planted Ha	1000 ha	128.75	128.75	128.75	128.72	128.75	128.75
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,935,084.53	2,938,403.68	2,940,321.56	2,758,451.42	2,938,403.68	2,939,827.86
Net Electricity	1000 kWh	3,214,117.37	3,217,436.52	3,219,354.40	3,037,484.26	3,217,436.52	3,218,860.70
Carbon Offset @ Eth	ton	582.40	582.40	582.40	582.40	582.40	582.40
Carbon Offset @ Elec	ton	2,568,628.46	2,553,467.39	2,538,703.04	2,623,328.85	2,553,467.39	2,538,890.45
Net Reduction	ton	2,922,518.62	2,907,357.56	2,892,593.21	2,977,219.02	2,907,357.56	2,892,780.62
SWP Subsidy	Million NT	6437.46	6437.42	6437.34	6435.93	6437.42	6437.38
SWP Planted Ha	1000 ha	128.75	128.75	128.75	128.72	128.75	128.75

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	20	20	20	25	25	25
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	25	25	25	25	25	25
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,857,590.26	2,839,035.56	2,766,419.16	2,758,567.6	2,839,256.4	2,821,662.43
Net Electricity	1000 kWh	3,136,623.1	3,118,068.4	3,045,452	3,037,600.44	3,118,289.23	3,100,695.27
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,449,633.88	2,477,375.76	2,480,880.38	2,522,151.71	2,477,198.31	2,458,926.86
Net Reduction	ton	2,803,524.05	2,831,265.93	2,834,770.55	2,876,041.88	2,831,088.48	2,812,817.02
SWP Subsidy	Million NT	6171.34	6216.53	6215.75	6169.76	6217.39	6208.44
SWP Planted Ha	1000 ha	123.43	124.33	124.31	123.4	124.35	124.17
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	2,857,590.26	2,838,892.21	2,766,422.83	2,758,567.6	2,838,891.97	2,838,153.46
Net Electricity	1000 kWh	3,136,623.1	3,117,925.05	3,045,455.67	3,037,600.44	3,117,924.81	3,117,186.3
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,449,633.88	2,477,219.45	2,484,047.38	2,522,151.71	2,477,219.46	2,447,892.39
Net Reduction	ton	2,803,524.05	2,831,109.61	2,837,937.55	2,876,041.88	2,831,109.62	2,801,782.56
SWP Subsidy	Million NT	6171.34	6218.04	6220.46	6169.76	6218.04	6199.58
SWP Planted Ha	1000 ha	123.43	124.36	124.41	123.4	124.36	123.99

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	30	30	30	35	35	35
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	25	25	25	25	25	25
Scenario A2							
Ethanol Production	1000 L	20,280	5200	20,280	58,367.86	23,726.68	61,314.1
Pyrolysis Electricity	1000 kWh	2,679,060.96	2,839,256.38	2,654,344.03	2,638,218.23	2,762,500	2,649,692.03
Net Electricity	1000 kWh	2,958,093.79	3,118,289.22	2,933,376.87	2,917,251.07	3,041,532.84	2,928,724.87
Carbon Offset @ Eth	ton	2271.36	582.4	2271.36	6537.2	2657.39	6867.18
Carbon Offset @ Elec	ton	2,384,691.76	2,477,198.31	2,364,736.24	2,033,403.66	2,322,265.09	1,977,417.21
Net Reduction	ton	2,740,270.88	2,831,088.48	2,720,315.37	2,393,248.63	2,678,230.24	2,337,592.16
SWP Subsidy	Million NT	6209.45	6217.39	6208.44	6215.94	6213.46	6220.38
SWP Planted Ha	1000 ha	124.19	124.35	124.17	124.32	124.27	124.41
Scenario B2							
Ethanol Production	1000 L	20,280	5200	20,280	58,367.86	26,011.35	44,670.05
Pyrolysis Electricity	1000 kWh	2,679,060.96	2,838,791.47	2,670,835.06	2,638,218.23	2,762,500	2,629,227.74
Net Electricity	1000 kWh	2,958,093.79	3,117,824.31	2,949,867.9	2,917,251.07	3,041,532.84	2,908,260.58
Carbon Offset @ Eth	ton	2271.36	582.4	2271.36	6537.2	2913.27	5003.05
Carbon Offset @ Elec	ton	2,384,691.76	2,477,167.55	2,353,701.77	2,033,403.66	2,299,148.92	2,192,015.29
Net Reduction	ton	2,740,270.88	2,831,057.72	2,709,280.9	2,393,248.63	2,655,369.96	2,550,326.1
SWP Subsidy	Million NT	6209.45	6218.66	6199.58	6215.94	6221.28	6317.6
SWP Planted Ha	1000 ha	124.19	124.37	123.99	124.32	124.43	126.35

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	40	40	40	20	20	20
Coal Price	NT/kg	1.8	1.8	1.8	3.6	3.6	3.6
GHG Price	NT/ton	25	25	25	25	25	25
Scenario A2							
Ethanol Production	1000 L	144,663.6	130,000	142,091.12	5200	5200	5200
Pyrolysis Electricity	1000 kWh	1,680,681.86	1,826,455.54	1,443,907.48	3,484,411.9	3,465,020.77	3,426,113.7
Net Electricity	1000 kWh	1,959,714.7	2,105,488.38	1,722,940.32	3,763,444.74	3,744,053.61	3,705,146.54
Carbon Offset @ Eth	ton	16,202.32	14,560	15,914.21	582.4	582.4	582.4
Carbon Offset @ Elec	ton	1,494,468.64	1,582,073.05	1,637,906.03	2,294,511.77	2,283,242.57	2,259,102.13
Net Reduction	ton	1,863,978.73	1,949,940.82	2,007,128	2,648,401.94	2,637,132.74	2,612,992.3
SWP Subsidy	Million NT	6216.02	6222.63	6367.68	6197.46	6222.6	6188.58
SWP Planted Ha	1000 ha	124.32	124.45	127.35	123.95	124.45	123.77

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Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Scenario B2							
Ethanol Production	1000 L	144,663.6	130,000	141,872.22	5200	5200	5200
Pyrolysis Electricity	1000 kWh	1,680,681.86	1,926,447.73	1,420,678.4	3,484,411.9	3,462,276.93	3,424,847.45
Net Electricity	1000 kWh	1,959,714.7	2,205,480.57	1,699,711.24	3,763,444.74	3,741,309.77	3,703,880.29
Carbon Offset @ Eth	ton	16,202.32	14,560	15,889.69	582.4	582.4	582.4
Carbon Offset @ Elec	ton	1,494,468.64	1,551,245.66	1,619,821.18	2,294,511.77	2,281,434.57	2,258,267.21
Net Reduction	ton	1,863,978.73	1,919,113.42	1,989,018.64	2,648,401.94	2,635,324.74	2,612,157.38
SWP Subsidy	Million NT	6216.02	6222.68	6307.89	6197.46	6218.92	6186.75
SWP Planted Ha	1000 ha	124.32	124.45	126.16	123.95	124.38	123.74

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	25	25	25	30	30	30
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	25	25	25	25	25	25
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	3,456,531.6	3,459,683.51	3,426,113.7	3,484,076.28	3,459,713.52	3,426,113.7
Net Electricity	1000 kWh	3,735,564.44	3,738,716.35	3,705,146.54	3,763,109.12	3,738,746.36	3,705,146.54
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,276,152.42	2,279,725.68	2,259,102.13	2,294,290.76	2,279,745.45	2,259,102.13
Net Reduction	ton	2,630,042.59	2,633,615.85	2,612,992.3	2,648,180.93	2,633,635.62	2,612,992.3
SWP Subsidy	Million NT	6188.05	6214.99	6188.58	6199.86	6215.03	6188.58
SWP Planted Ha	1000 ha	123.76	124.3	123.77	124	124.3	123.77
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	3,456,531.6	3,464,975.72	3,424,847.45	3,484,076.28	3,460,456.11	3,424,847.45
Net Electricity	1000 kWh	3,735,564.44	3,744,008.56	3,703,880.29	3,763,109.12	3,739,488.95	3,703,880.29
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,276,152.42	2,283,212.89	2,258,267.21	2,294,290.76	2,280,234.77	2,258,267.21
Net Reduction	ton	2,630,042.59	2,637,103.05	2,612,157.38	2,648,180.93	2,634,124.94	2,612,157.38
SWP Subsidy	Million NT	6188.05	6222.54	6186.75	6199.86	6216.04	6186.75
SWP Planted Ha	1000 ha	123.76	124.45	123.74	124	124.32	123.74

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	35	35	35	40	40	40
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	25	25	25	25	25	25
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	3,484,076.28	3,465,022.03	3,434,688.26	3,434,688.26	3,461,704.19	3,434,688.26
Net Electricity	1000 kWh	3,763,109.12	3,744,054.86	3,713,721.1	3,713,721.1	3,740,737.03	3,713,721.1
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,294,290.76	2,283,243.4	2,264,755.87	2,264,755.87	2,281,057.17	2,264,755.87
Net Reduction	ton	2,648,180.93	2,637,133.57	2,618,646.04	2,618,646.04	2,634,947.34	2,618,646.04
SWP Subsidy	Million NT	6199.86	6222.61	6202.37	6202.37	6217.83	6202.37
SWP Planted Ha	1000 ha	124	124.45	124.05	124.05	124.36	124.05
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	5200	5200	5200
Pyrolysis Electricity	1000 kWh	3,484,076.28	3,465,087.84	3,433,210.63	3,434,688.26	3,462,276.93	3,433,210.63
Net Electricity	1000 kWh	3,763,109.12	3,744,120.68	3,712,243.47	3,713,721.1	3,741,309.77	3,712,243.47
Carbon Offset @ Eth	ton	582.4	582.4	582.4	582.4	582.4	582.4
Carbon Offset @ Elec	ton	2,294,290.76	2,283,286.77	2,263,781.58	2,264,755.87	2,281,434.57	2,263,781.58
Net Reduction	ton	2,648,180.93	2,637,176.93	2,617,671.75	2,618,646.04	2,635,324.74	2,617,671.75
SWP Subsidy	Million NT	6199.86	6222.73	6200.14	6202.37	6218.92	6200.14
SWP Planted Ha	1000 ha	124	124.45	124	124.05	124.38	124

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	20	20	20	25	25	25
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	5	5	5	5	5	5
Scenario A2							
Ethanol Production	1000 L	68,226.94	60,178.14	64,703.95	132,600	130,000	132,600
Pyrolysis Electricity	1000 kWh	2,497,300	2,762,500	2,497,300	1,836,090.06	2,057,980.76	1,836,090.06
Net Electricity	1000 kWh	2,776,332.84	3,041,532.84	2,776,332.84	2,115,122.9	2,337,013.6	2,115,122.9
Carbon Offset @ Eth	ton	7641.42	6739.95	7246.84	14,851.2	14,560	14,851.2
Carbon Offset @ Elec	ton	1,669,537.68	1,818,830	1,669,537.68	1,227,184	1,356,762.74	1,227,184
Net Reduction	ton	2,030,486.87	2,178,877.72	2,030,092.29	1,595,342.97	1,724,630.51	1,595,342.97
SWP Subsidy	Million NT	5971.55	6018.07	5963.11	5990.08	6010.2	5990.08
SWP Planted Ha	1000 ha	119.43	120.36	119.26	119.8	120.2	119.8
Scenario B2							
Ethanol Production	1000 L	68,226.94	59,957.71	64,605.48	132,600	130,000	132,600
Pyrolysis Electricity	1000 kWh	2,497,300	2,762,500	2,497,300	1,836,090.06	2,061,388.24	1,834,995.65
Net Electricity	1000 kWh	2,776,332.84	3,041,532.84	2,776,332.84	2,115,122.9	2,340,421.08	2,114,028.48
Carbon Offset @ Eth	ton	7641.42	6715.26	7235.81	14,851.2	14,560	14,851.2
Carbon Offset @ Elec	ton	1,669,537.68	1,818,830	1,669,537.68	1,227,184	1,359,008.03	1,226,451.83

(*continued*)

Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Net Reduction	ton	2,030,486.87	2,178,853.03	2,030,081.26	1,595,342.97	1,726,875.8	1,594,610.8
SWP Subsidy	Million NT	5971.55	6015.06	5961.53	5990.08	6014.78	5988.27
SWP Planted Ha	1000 ha	119.43	120.3	119.23	119.8	120.3	119.77
Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	30	30	30	35	35	35
Coal Price	NT/kg	1.8	1.8	1.8	1.8	1.8	1.8
GHG Price	NT/ton	5	5	5	5	5	5
Scenario A2							
Ethanol Production	1000 L	132,600	130,000	132,600	170,987.24	130,000	171,270.34
Pyrolysis Electricity	1000 kWh	1,872,017.55	2,058,693.59	1,836,090.06	1,640,762.87	2,060,324.17	1,601,808.66
Net Electricity	1000 kWh	2,151,050.39	2,337,726.43	2,115,122.9	1,919,795.71	2,339,357.01	1,880,841.5
Carbon Offset @ Eth	ton	14,851.2	14,560	14,851.2	19,150.57	14,560	19,182.28
Carbon Offset @ Elec	ton	1,251,219.72	1,357,232.45	1,227,184	1,096,508.86	1,358,306.88	1,070,448.24
Net Reduction	ton	1,619,378.69	1,725,100.21	1,595,342.97	1,468,967.2	1,726,174.65	1,442,938.29
SWP Subsidy	Million NT	5999.34	6012.73	5990.08	6003.14	6014.52	5989.24
SWP Planted Ha	1000 ha	119.99	120.25	119.8	120.06	120.29	119.78
Scenario B2							
Ethanol Production	1000 L	132,600	130,000	132,600	170,987.24	130,000	171,259.63
Pyrolysis Electricity	1000 kWh	1,872,017.55	2,054,731.79	1,834,952.67	1,640,762.87	2,056,449.67	1,600,751.1
Net Electricity	1000 kWh	2,151,050.39	2,333,764.63	2,113,985.51	1,919,795.71	2,335,482.5	1,879,783.94
Carbon Offset @ Eth	ton	14,851.2	14,560	14,851.2	19,150.57	14,560	19,181.08
Carbon Offset @ Elec	ton	1,251,219.72	1,354,621.89	1,226,423.08	1,096,508.86	1,355,753.85	1,069,740.73
Net Reduction	ton	1,619,378.69	1,722,489.65	1,594,582.04	1,468,967.2	1,723,621.62	1,442,229.57
SWP Subsidy	Million NT	5999.34	6007.17	5988.2	6003.14	6009.48	5987.49
SWP Planted Ha	1000 ha	119.99	120.14	119.76	120.06	120.19	119.75
Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	40	40	40	20	20	20
Coal Price	NT/kg	1.8	1.8	1.8	3.6	3.6	3.6
GHG Price	NT/ton	5	5	5	5	5	5
Scenario A2							
Ethanol Production	1000 L	170,956.95	156,000	171,269.91	5200	5200	5200
Pyrolysis Electricity	1000 kWh	1,637,704.31	1,796,624.5	1,601,766.91	3,480,883.66	3,412,974.13	3,383,047.15
Net Electricity	1000 kWh	1916737.15	2,075,657.34	1,880,799.75	3,759,916.5	3,692,006.96	3,662,079.99
Carbon Offset @ Eth	ton	19,147.18	17,472	19,182.23	582.4	582.4	582.4
Carbon Offset @ Elec	ton	1,094,462.66	1,184,685.05	1,070,420.31	2,292,188.4	2,248,947.35	2,227,398.24
Net Reduction	ton	1,466,917.61	1,555,464.82	1,442,910.31	2,646,078.56	2,602,837.51	2,581,288.41
SWP Subsidy	Million NT	5998.47	6009.71	5989.18	6222.85	6154.63	6127.09
SWP Planted Ha	1000 ha	119.97	120.19	119.78	124.46	123.09	122.54
Scenario B2							
Ethanol Production	1000 L	170,956.95	156,000	171,259.63	5200	5200	5200
Pyrolysis Electricity	1000 kWh	1,637,704.31	1,794,399.17	1,600,751.1	3,480,883.66	3,450,662.05	3,382,385.07
Net Electricity	1000 kWh	1,916,737.15	2,073,432.01	1,879,783.94	3,759,916.5	3,729,694.88	3,661,417.91
Carbon Offset @ Eth	ton	19,147.18	17,472	19,181.08	582.4	582.4	582.4
Carbon Offset @ Elec	ton	1,094,462.66	1,183,218.71	1,069,740.73	2,292,188.4	2,273,781.14	2,226,962.33
Net Reduction	ton	1,466,917.61	1,553,998.48	1,442,229.57	2,646,078.56	2,627,671.31	2,580,852.5
SWP Subsidy	Million NT	5998.47	6007.79	5987.49	6222.85	6202.33	6127.83
SWP Planted Ha	1000 ha	119.97	120.16	119.75	124.46	124.05	122.56
Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	25	25	25	30	30	30
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	5	5	5	5	5	5
Scenario A2							
Ethanol Production	1000 L	5200	5200	5200	64,037.96	70,465.59	59,172.77
Pyrolysis Electricity	1000 kWh	3,481,978.53	3,432,763.69	3,383,670.09	2,824,407.26	2,762,500	2,497,300
Net Electricity	1000 kWh	3,761,011.37	3,711,796.53	3,662,702.93	3,103,440.1	3,041,532.84	2,776,332.84
Carbon Offset @ Eth	ton	582.4	582.4	582.4	7172.25	7892.15	6624.17
Carbon Offset @ Elec	ton	2,292,909.38	2,261,987.33	2,227,808.38	1,859,589.74	1,818,830	1,669,657.84
Net Reduction	ton	2,646,799.54	2,615,877.5	2,581,698.55	2,220,069.76	2,180,029.91	2,029,589.78
SWP Subsidy	Million NT	6214.89	6180.39	6127.9	6130.25	6154.15	5740.37
SWP Planted Ha	1000 ha	124.3	123.61	122.56	122.61	123.08	114.81
Scenario B2							
Ethanol Production	1000 L	5200	5200	5200	64,037.96	72,721.69	59,080.88
Pyrolysis Electricity	1000 kWh	3,481,978.53	3,425,596.92	3,359,244.58	2,824,407.26	2,762,500	2,497,300
Net Electricity	1000 kWh	3,761,011.37	3,704,629.76	3,638,277.42	3,103,440.1	3,041,532.84	2,776,332.84
Carbon Offset @ Eth	ton	582.4	582.4	582.4	7172.25	8144.83	6613.88
Carbon Offset @ Elec	ton	2,292,909.38	2,257,264.91	2,211,726.63	1,859,589.74	1,818,830	1,669,657.84
Net Reduction	ton	2,646,799.54	2,611,155.08	2,565,616.8	2,220,069.76	2,180,282.6	2,029,579.49
SWP Subsidy	Million NT	6214.89	6169.27	6095.46	6130.25	6184.35	5738.88
SWP Planted Ha	1000 ha	124.3	123.39	121.91	122.61	123.69	114.78
Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	35	35	35	40	40	40

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Probability of Yield Change		Low	Moderate	High	Low	Moderate	High
Coal Price	NT/kg	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	5	5	5	5	5	5
Scenario A2							
Ethanol Production	1000 L	83,563.87	71,667.39	76,300.06	97,579.35	74,686.34	94,062.34
Pyrolysis Electricity	1000 kWh	2,669,296.28	2,762,500	2,668,096.23	2,497,300	2,762,500	2,497,300
Net Electricity	1000 kWh	2,948,329.12	3,041,532.84	2,947,129.07	2,776,332.84	3,041,532.84	2,776,332.84
Carbon Offset @ Eth	ton	9359.15	8026.75	8545.61	10,928.89	8364.87	10,534.98
Carbon Offset @ Elec	ton	1,766,361.68	1,818,830	1,765,686.12	1,669,537.68	1,818,830	1,669,537.68
Net Reduction	ton	2,129,028.6	2,180,164.52	2,127,539.49	2,033,774.34	2,180,502.64	2,033,380.43
SWP Subsidy	Million NT	6197.94	6170.27	6133.75	6174.96	6209.11	6164.32
SWP Planted Ha	1000 ha	123.96	123.41	122.67	123.5	124.18	123.29
Scenario B2							
Ethanol Production	1000 L	83,563.87	70,906.23	76,177.46	97,579.35	73,734.98	93,962.53
Pyrolysis Electricity	1000 kWh	2,669,296.28	2,762,500	2,667,943.56	2,497,300	2,762,500	2,497,300
Net Electricity	1000 kWh	2,948,329.12	3,041,532.84	2,946,976.4	2,776,332.84	3,041,532.84	2,776,332.84
Carbon Offset @ Eth	ton	9359.15	7941.5	8531.88	10,928.89	8258.32	10,523.8
Carbon Offset @ Elec	ton	1,766,361.68	1,818,830	1,765,600.17	1,669,537.68	1,818,830	1,669,537.68
Net Reduction	ton	2,129,028.6	2,180,079.27	2,127,439.81	2,033,774.34	2,180,396.09	2,033,369.25
SWP Subsidy	Million NT	6197.94	6159.54	6131.67	6174.96	6196.84	6162.79
SWP Planted Ha	1000 ha	123.96	123.19	122.63	123.5	123.94	123.26

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